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Laser Heating and Penetration of Aluminum Alloys at 0.8-micron Wavelength

S. Wu, J. Florando, S. Khairallah, M. LeBlanc, H. Lowdermilk, R. McCallen, A. Rubenchik, J. Stanley

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Laser Heating and Penetration of Aluminum Alloys at 0.8-micron Wavelength

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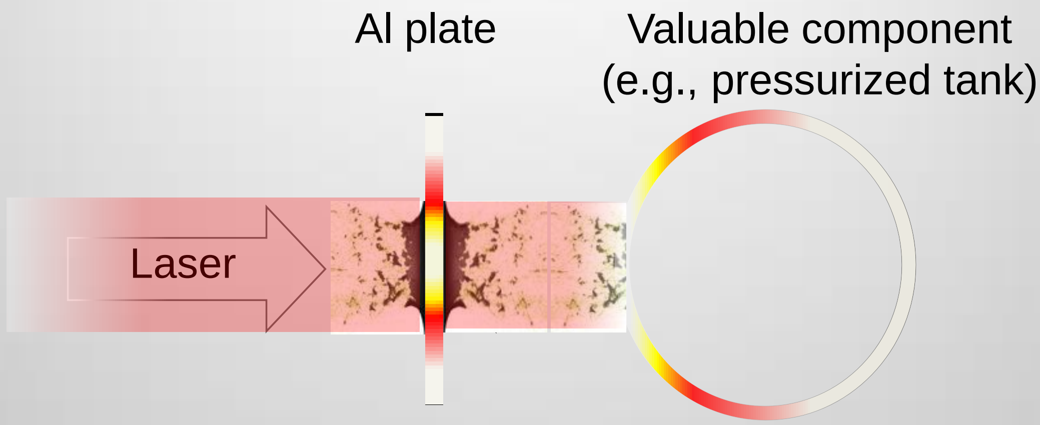
Abstract

We report on near-IR laser heating and penetration experiments where 1-mm thick aluminum samples are illuminated by 0.8 μm laser light at intensities up to 200 W/cm^2, levels that are much lower than those in typical laser lethality studies found in literature. At intensities below 150 W/cm^2, a thin layer of metal-oxide remains over the irradiated area after the underlying aluminum has melted. At intensities ~200 W/cm^2, fragments/droplets of material may be ejected forming an open hole in the material. The physics of these two regimes will be discussed. Failure physics and materials modeling as a function of heating rate are discussed.

Physics not previously explored experimentally or computationally

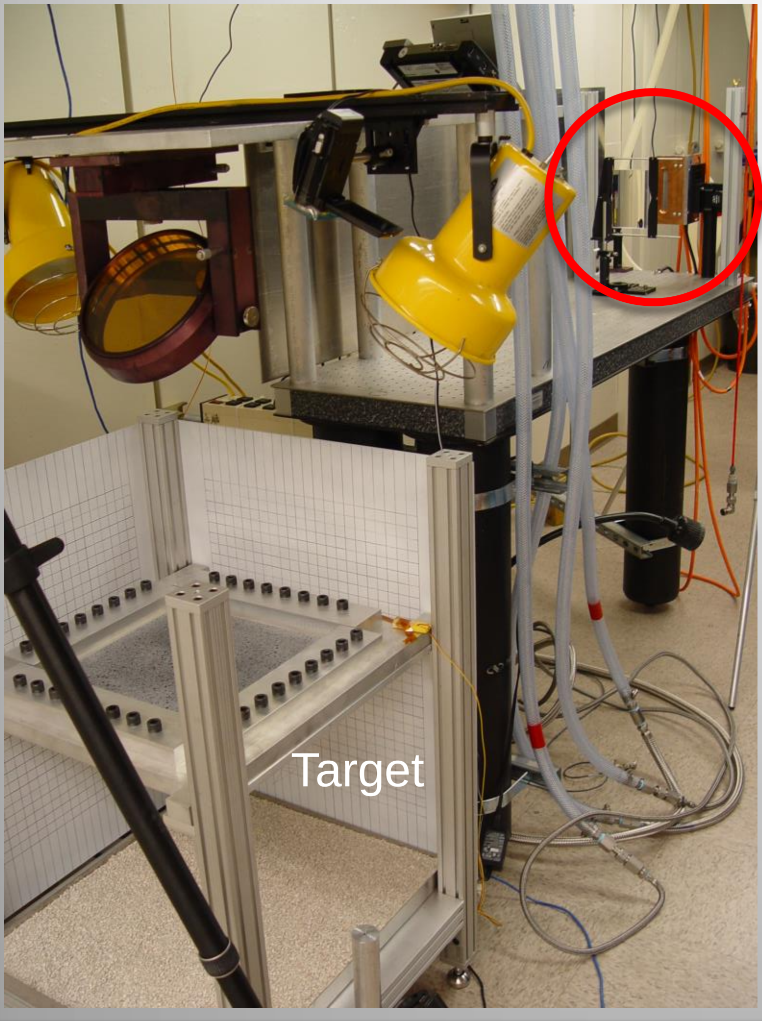


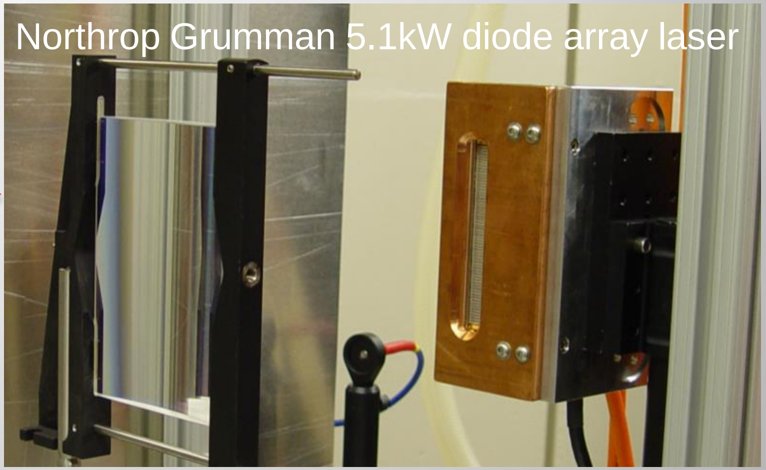
- Laser rupture/penetrate skin, clear path to the real target
- Potential path clearing phenomena:
  - Fragment velocity from release of mechanical/thermal stress
  - Thermally isolated fragments melt, reduce x-section by surface tension
  - Ablation recoil acceleration
- High velocity hot/liquid fragments may cause damage to sensitive electronics / pressure vessels

Motivation

- Key questions: how long does it take to clean the path? How does the melting process evolve? What physical process come into play?
- Need: development and validation of a predictive physics model for laser-material interaction phenomena with
  - Constrained or stressed mechanical states
  - Laser energy deposition
  - Material damage / failure
  - Path clearing

Experimental set-up

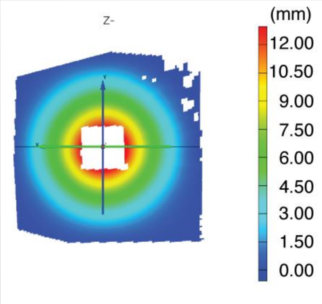


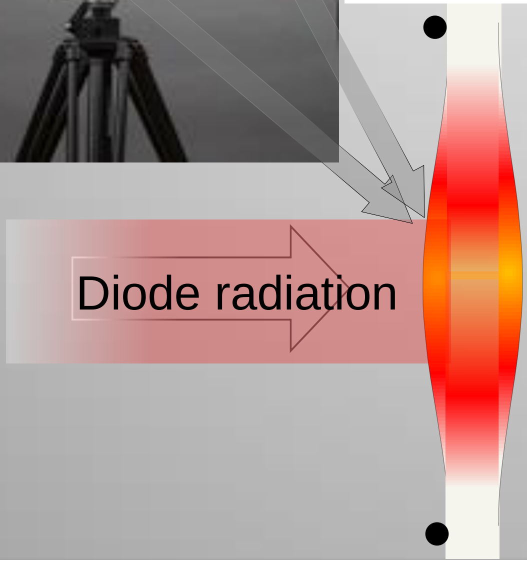


- 5.1 kW 60-bar diode array laser outputs CW radiation at 0.8 μm
- Compact, light-weight, relatively inexpensive surrogate light source
- Enables laboratory experiments at relevant irradiances for DE/DoD applications

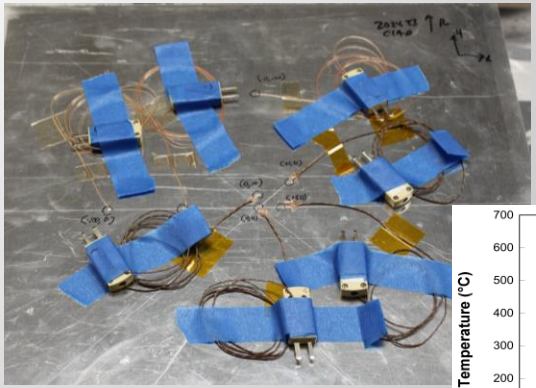
Diagnostics

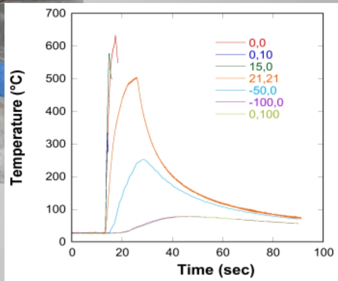
Surface distortion measured by Digital Image Correlation (DIC)



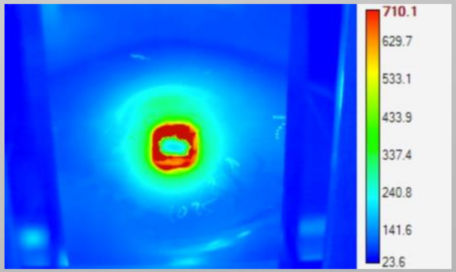


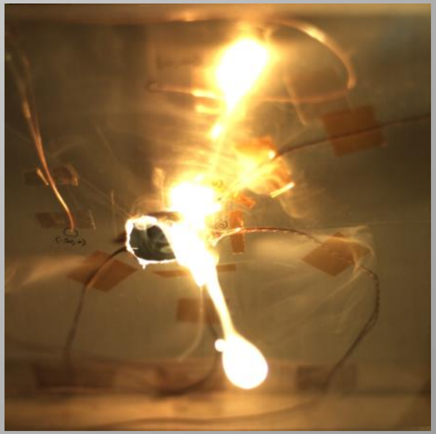
Thermocouples attached to back sides of plates



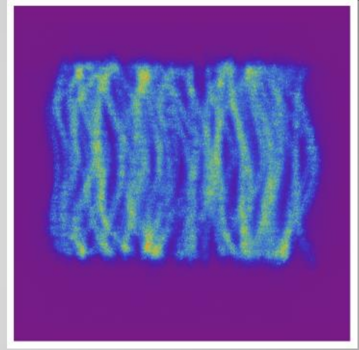


Thermal imaging and digital video cameras





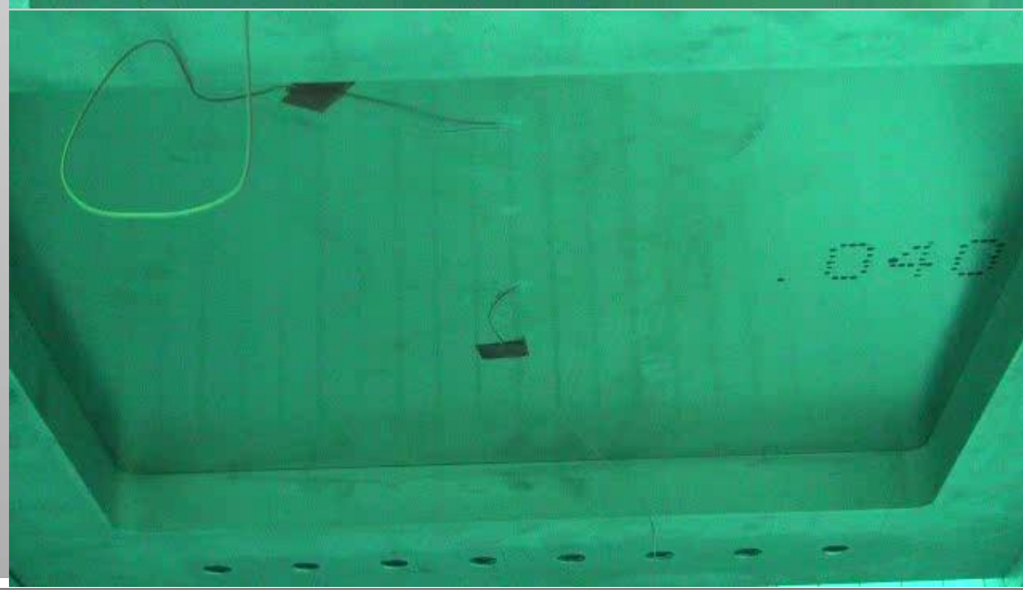
Al 7075 (horizontal) video



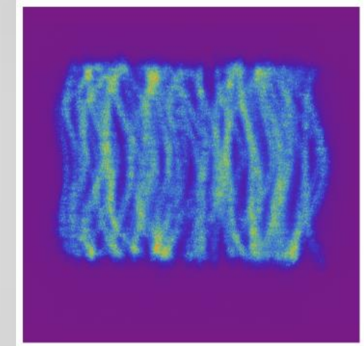
Average irradiance = 50 W/cm^2

Top view

Bottom

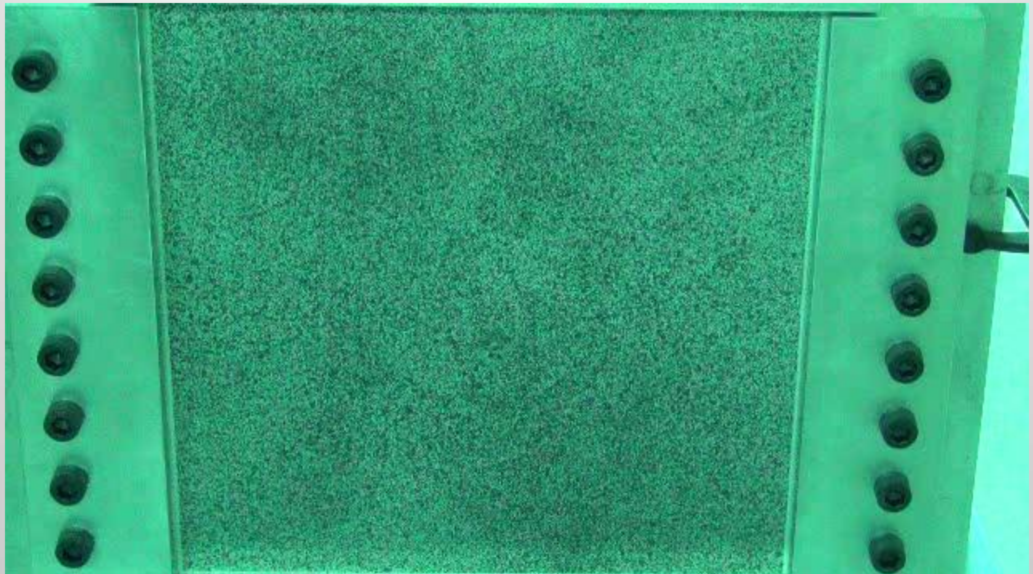


Al 2024 (vertical) video

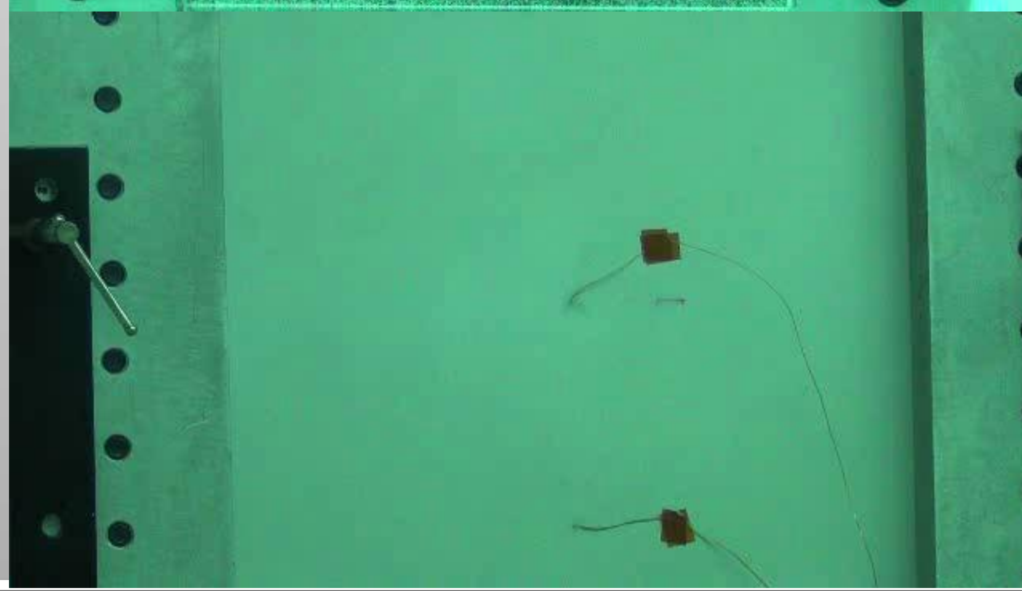


Average irradiance = 50 W/cm^2

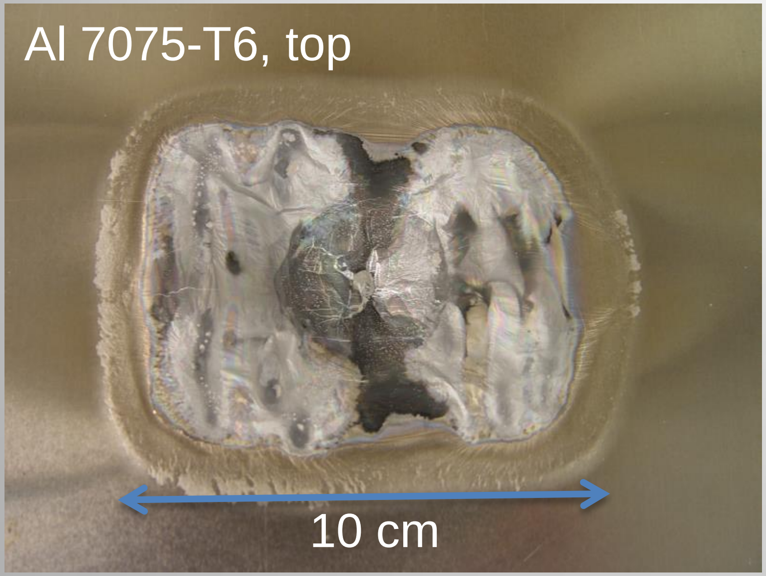
Top view

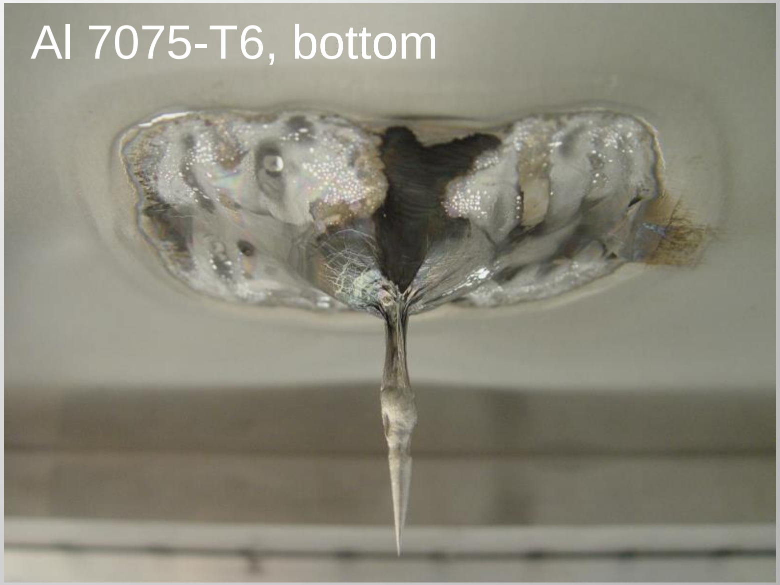


Bottom

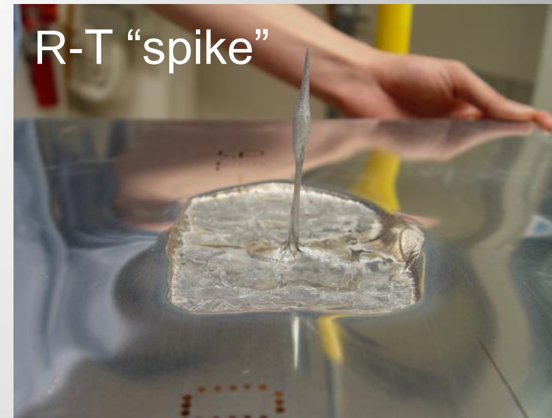


Oxide formation at low irradiance (50 W/cm^2)





- Diode irradiance was about 50 W/cm^2. Similar results were observed up to ~150 W/cm^2
- Laser heated for over a minute after initial surface modification with little change in morphology
- Observed in experiments with Al 2024-T3 and Al 7075-T6, clad/unclad, bare surface, bead blasted surface, painted/unpainted…
- Surface oxidation of Al is believed to be responsible



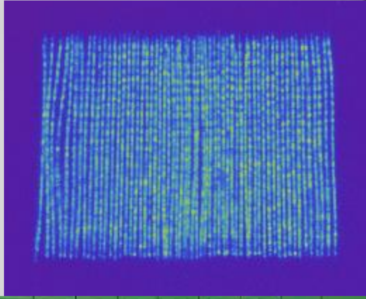
Analysis

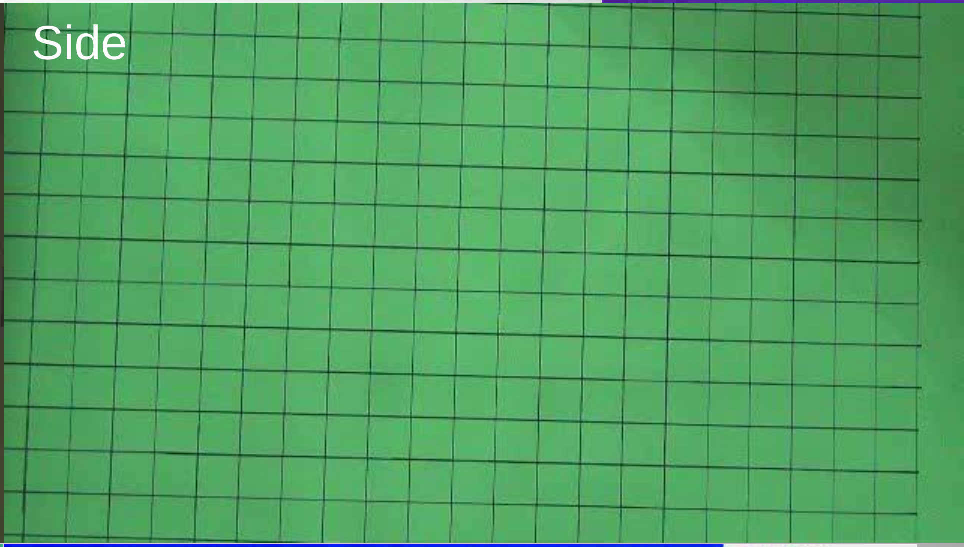
- The free surface of melt is unstable (Rayleigh-Taylor instability)
- To form a liquid droplet, the difference in potential energy must be larger than the surface energy of the droplet.
- For a falling droplet, the above gives a condition on the spot size a^2:

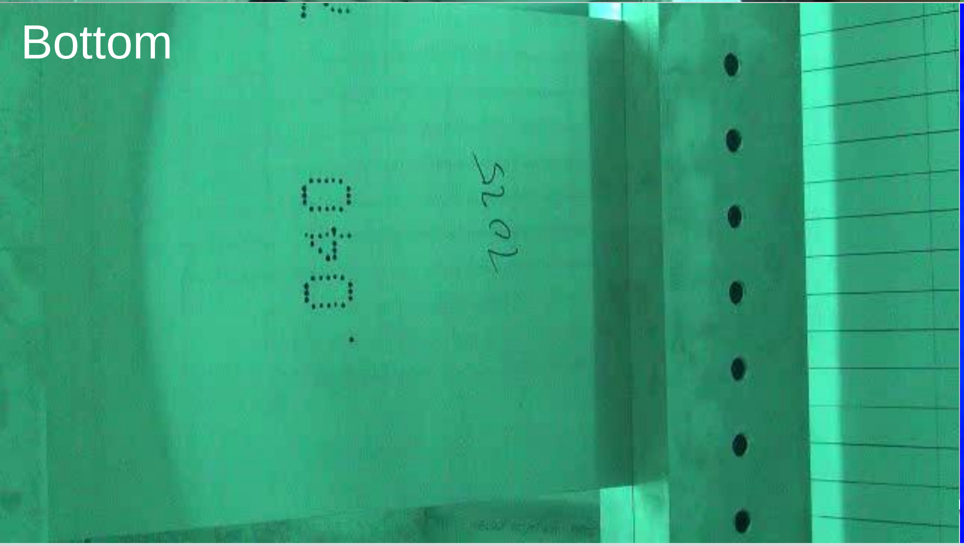
$$a^2 > \frac{4p\sqrt{3}}{h}\left(\frac{a}{r\,g}\right)^{3/2} \approx 50\ cm^2$$

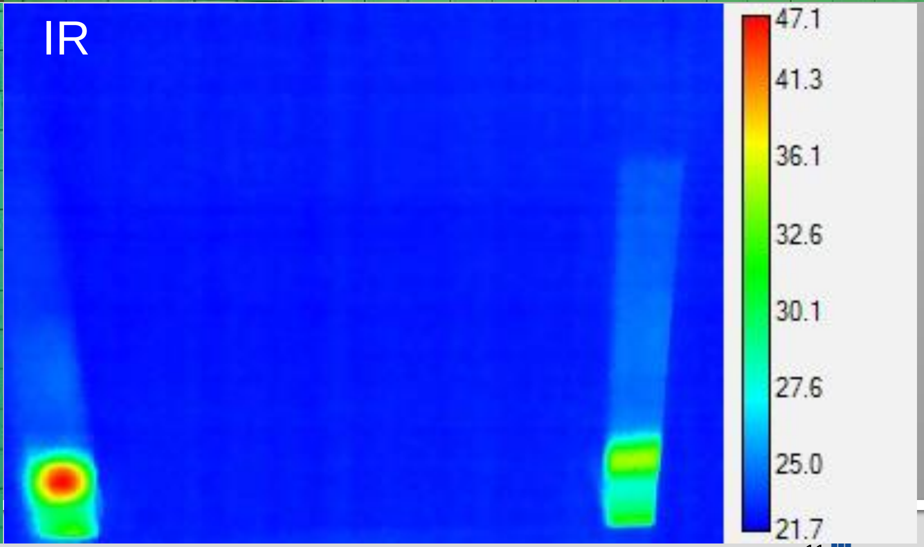
- We observed melt bulging for $a^2 \approx 20\ \text{cm}^2$ and droplet formation for $a^2 \approx 100\ \text{cm}^2$

Experiments at higher intensities
Al 7075 at ≈210 W/cm^2



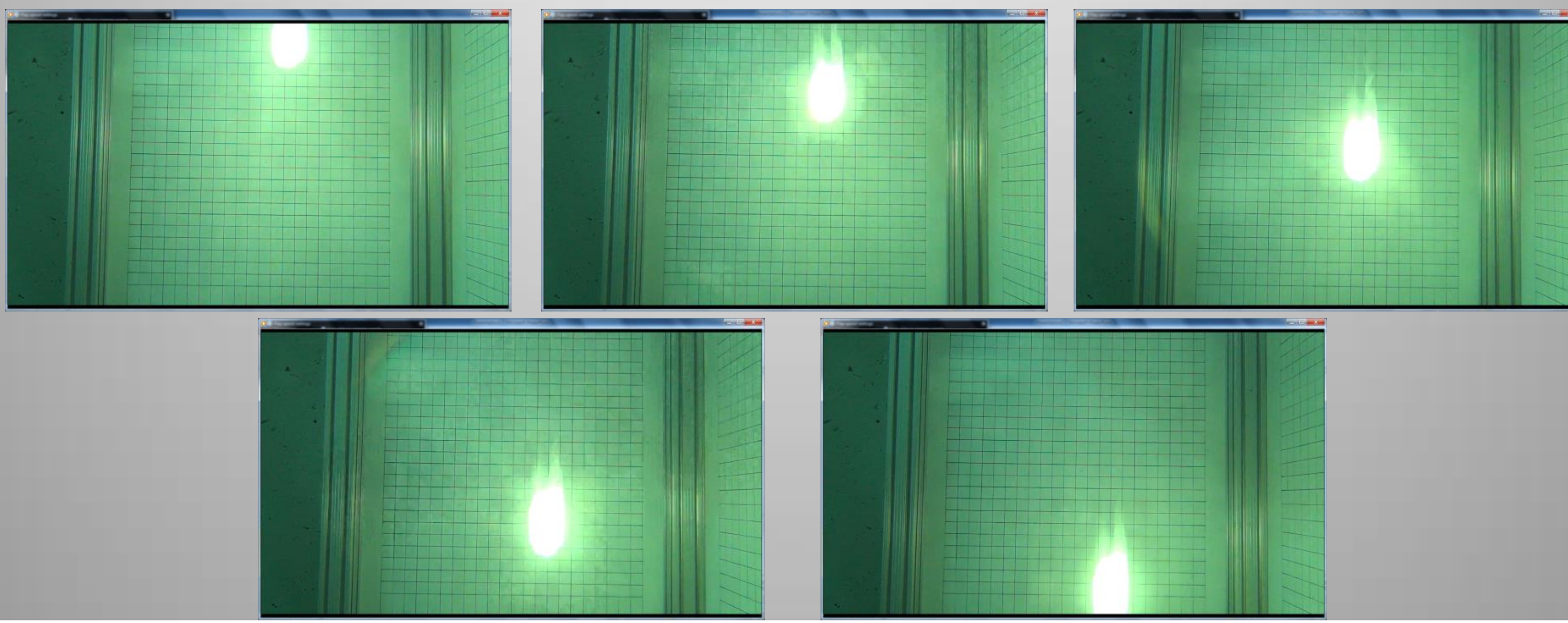




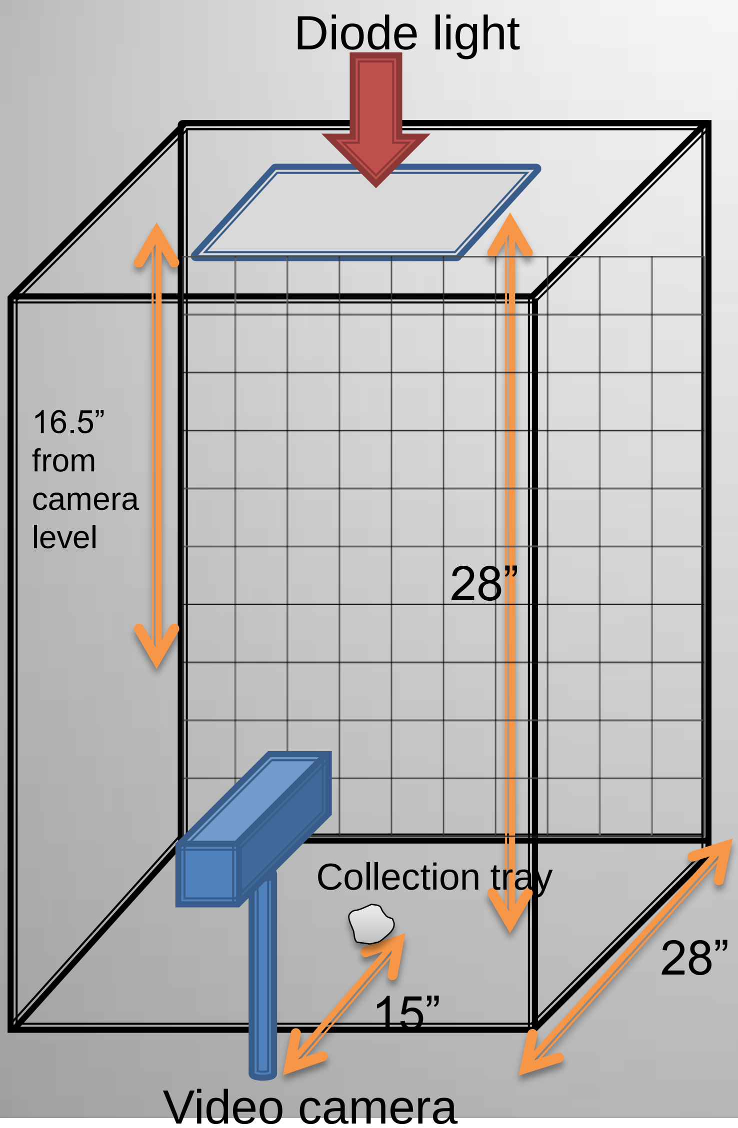


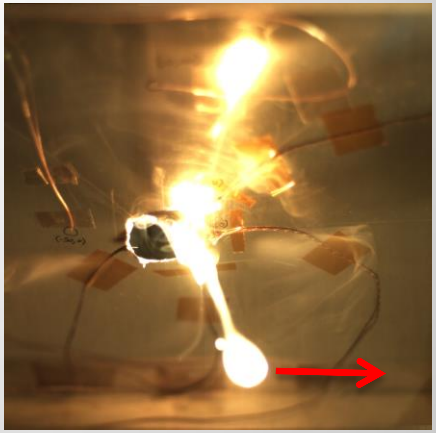
Determination of blob velocity

- We designed an experiment to isolate the effect of gravity
- By recording the the trajectory of the liquid, the initial velocity can be determined.

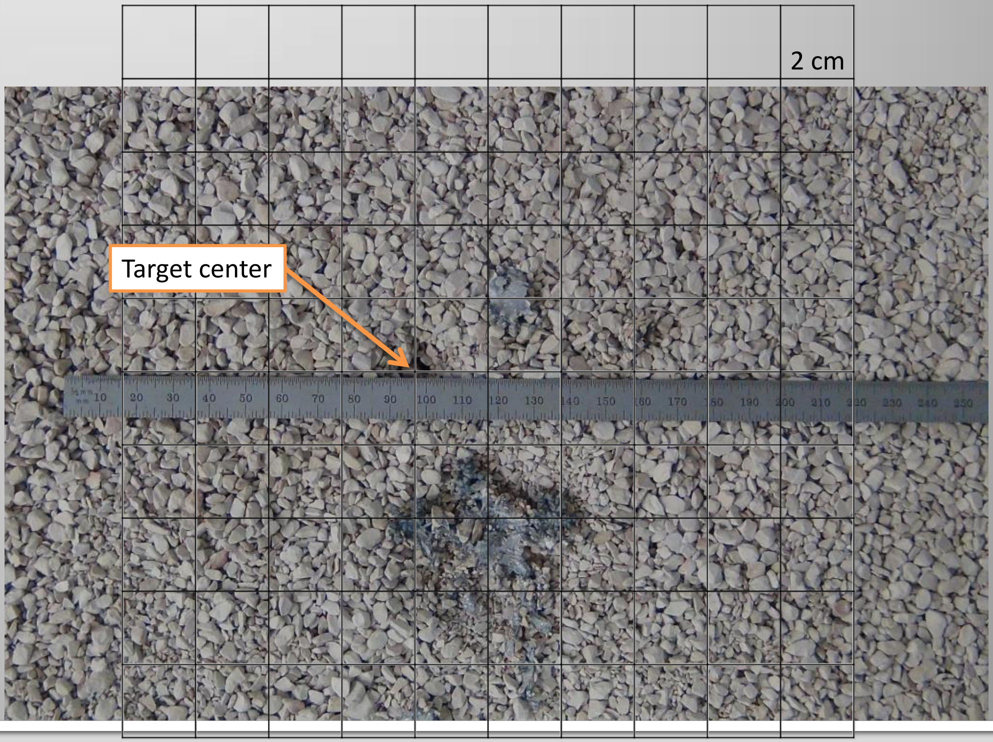


Experiment apparatus

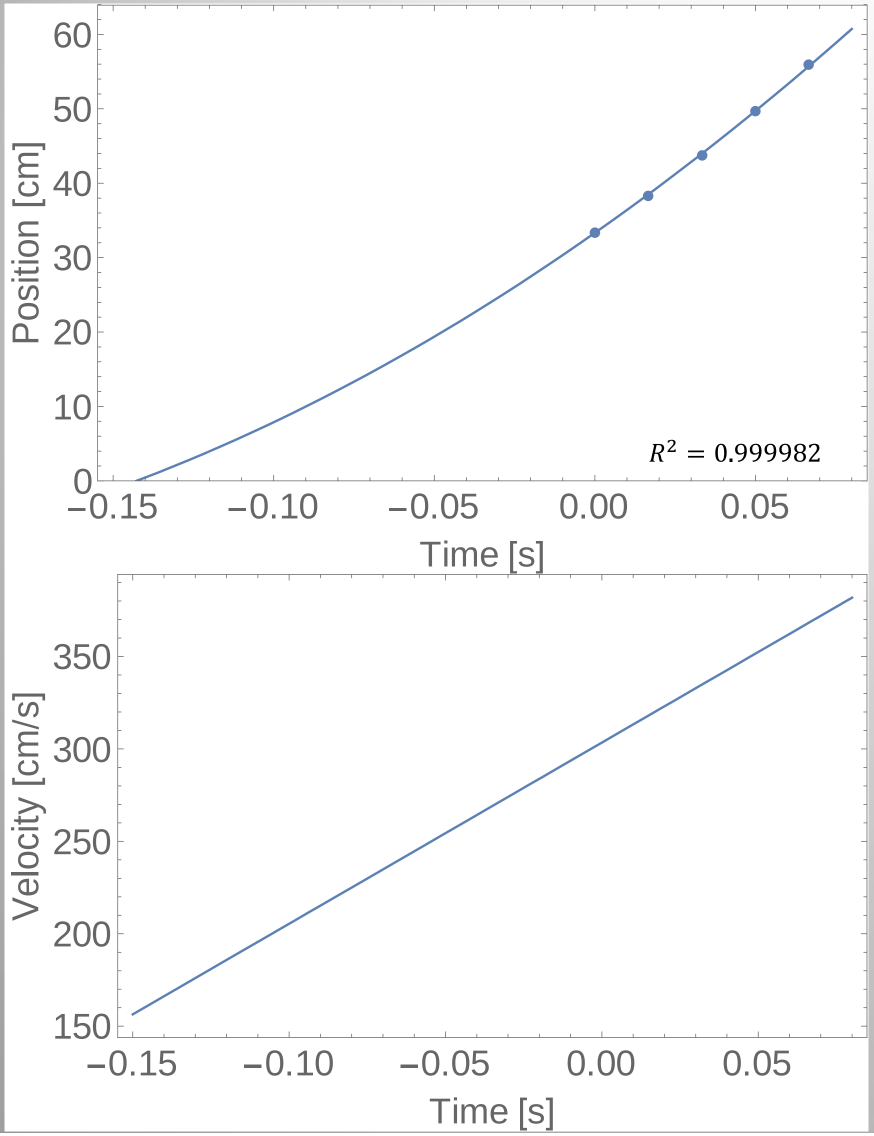




Nonzero
lateral
velocity



Free fall analysis



- Video captures several still frames where the fragment is observed.
- Assuming perfect free-fall, we can do a simple parabolic fit of vertical displacement:

$$y(t) = x(t_1) + v(t_1)t + \frac{1}{2}gt^2$$

- Estimated initial vertical velocity based on fit ≈ 160 cm/s
- Horizontal velocity ≈ 18 cm/s

Comparison of surface tension and gravitational forces

- Surface tension: $P = 2\alpha/R$ where $\alpha \approx 865\ \mathrm{dyne/cm}$ for Al
- For $R \sim 1\ cm$, $P \sim 2 \times 865\ \mathrm{dyne}/cm^2 = 173\ Pa$

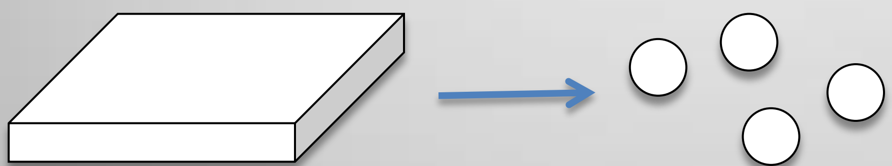
- Gravity: $P = \rho g h$
- For $h \sim 1\ mm$, $P \sim 2.7 \times 980 \times 0.1 = 264\ Pa$

- Comparable magnitudes → surface tension plays an important role

Why melt do not break into droplets

- Droplets form if it is energetically favorable. In this case, this means a reduction in the total surface area of the liquid.
- Suppose that the slab with volume S×h breaks into N spherical droplets of radius R_n

$$R_n = \left(\frac{3Sh}{4pN} \right)^{1/3}$$



$$N 4p R_n^{\ 2} = 4pN \left(\frac{3Sh}{4pN} \right)^{2/3} \sim N^{1/3}$$

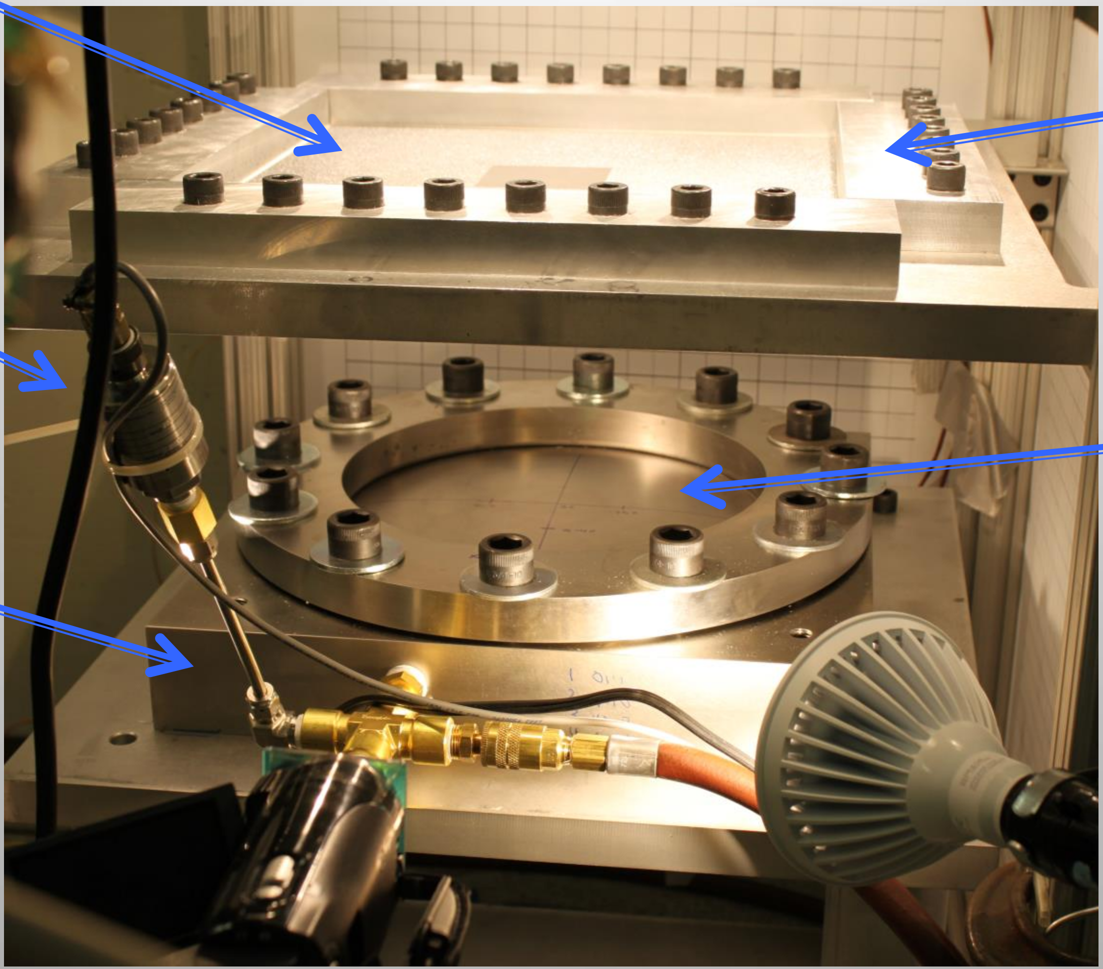
- The surface area minimizes for N = 1, hence the liquid film tends to form a *single* blob in the absence of other forces.
- Cross-section of a sphere is much less than that of a sheet (17% for S=20 cm^2), so this process effectively clears the laser path.
- The situation is different for a liquid cylinder. In this case it is more favorable to break into droplets.

Al plate and Ti pressure vessel experiment

Aluminum sheet

Pressure transducer

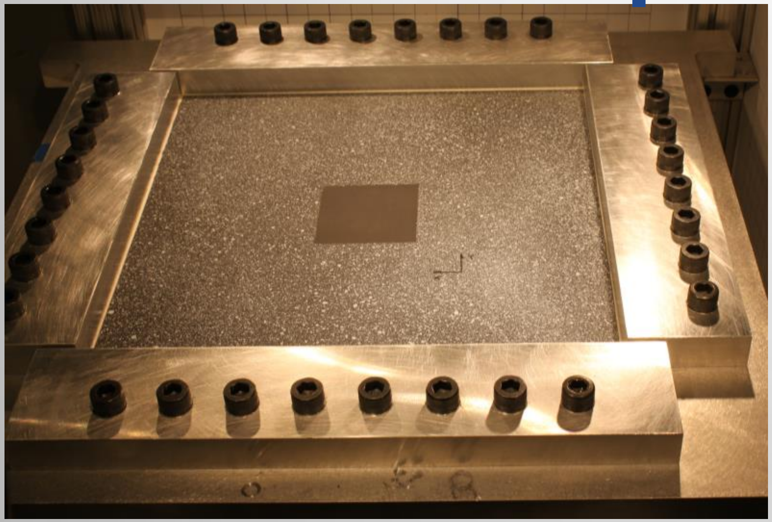
Pressure Vessel w/ 145 psig Ar



Constraint frame

Titanium plate

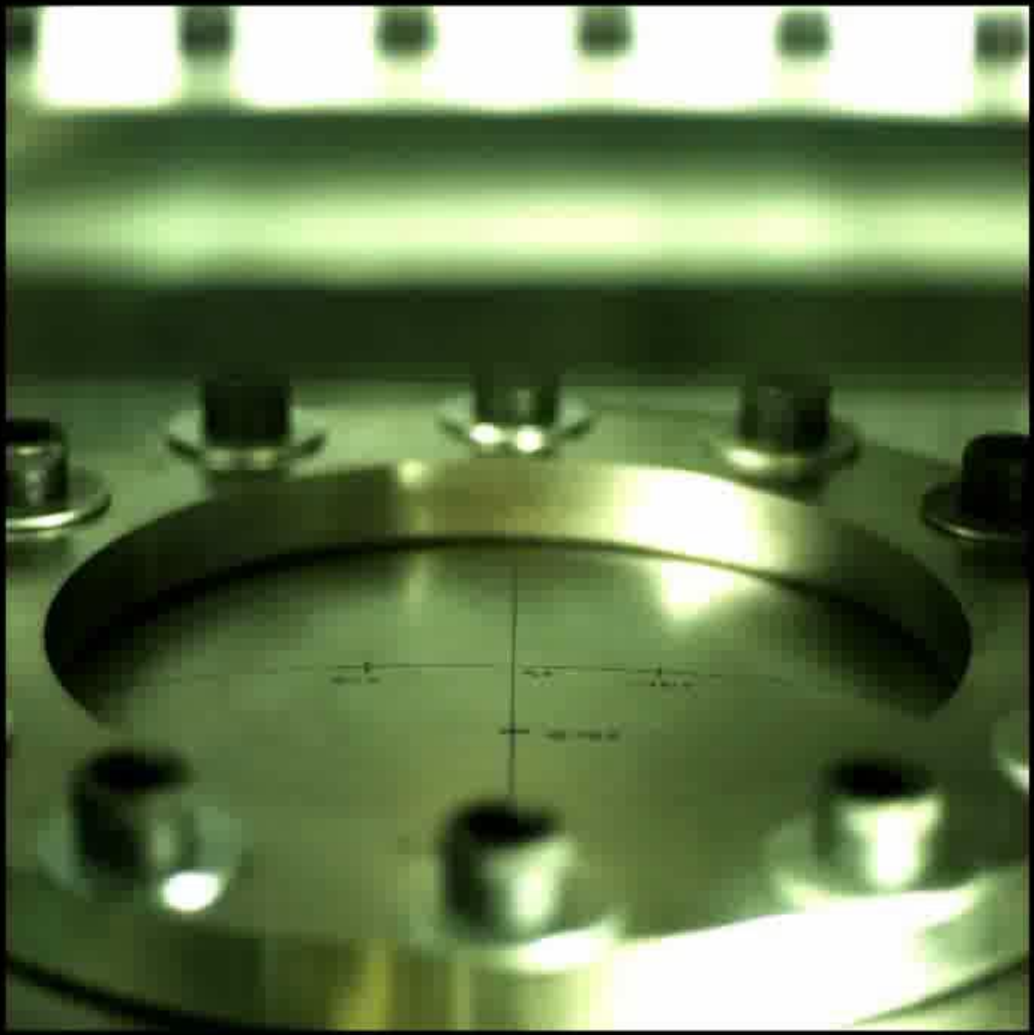
Pressurized experiment setup



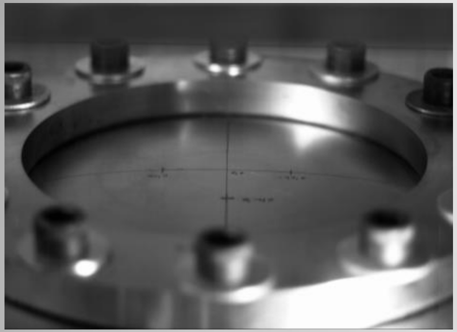
- Material: 2024-T3 (clad) sheet
  (381mm x 381mm x 1 mm)
- Edges constrained by clamping in frame
- Top side painted for DIC measurements
- Exposed area 330mm x 330mm

- Material: Ti-6Al-4V alloy
  (300mm dia. x 1 mm thick)
- Sheet was clamped into pressure vessel
- DIC measurements made during pre-test pressurization
- Rear side instrumented with four 36 gage, type K thermocouples

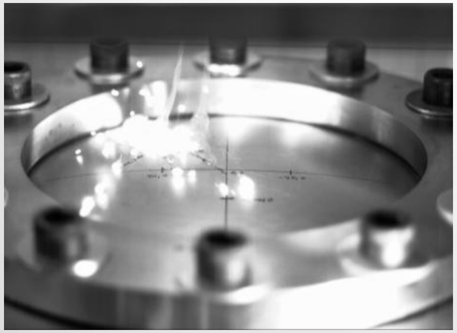
Pressurized Ti vessel experiment



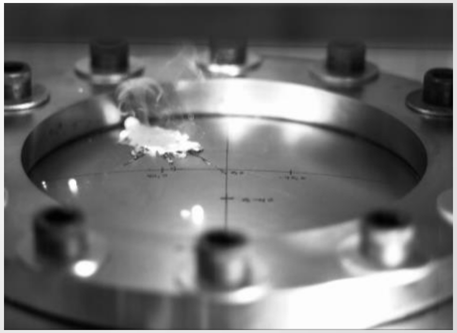
Results: Rupture of Ti plate (high speed photos 250 fr/sec)



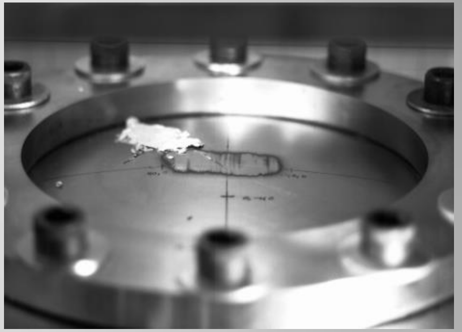
29.67 s (start)



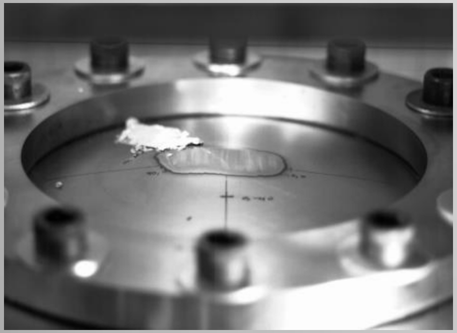
36.04 s (melt)



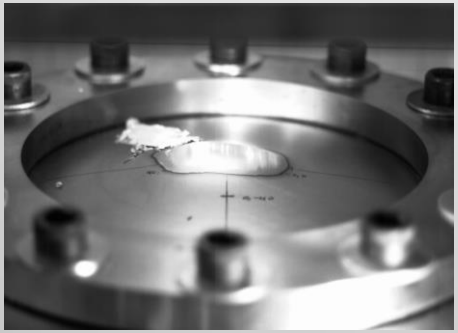
36.19 s



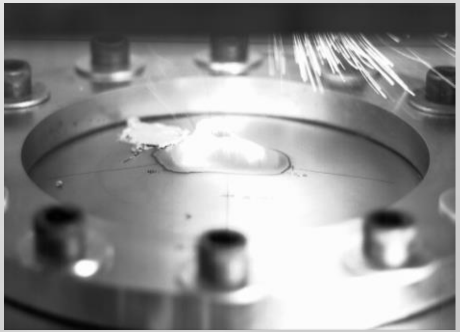
42.52 s



44.54 s

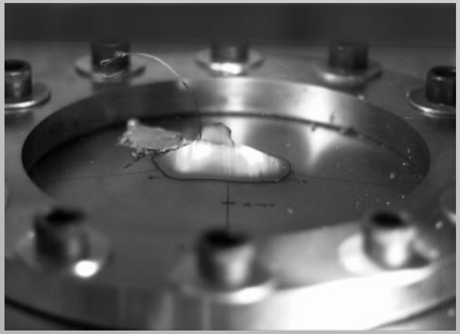


46.47 s



46.53 s (rupture)

46.60 s

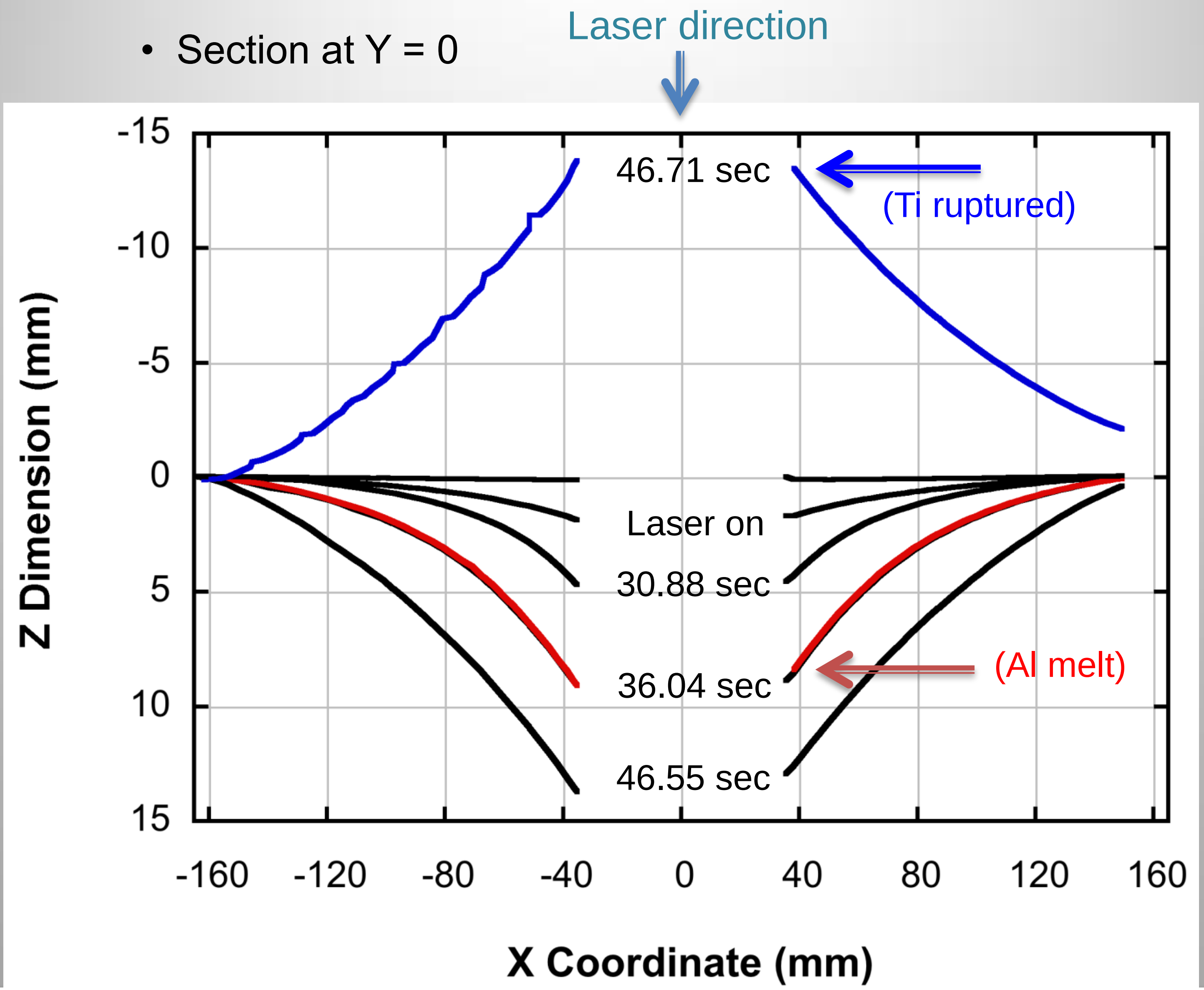


47.05 s

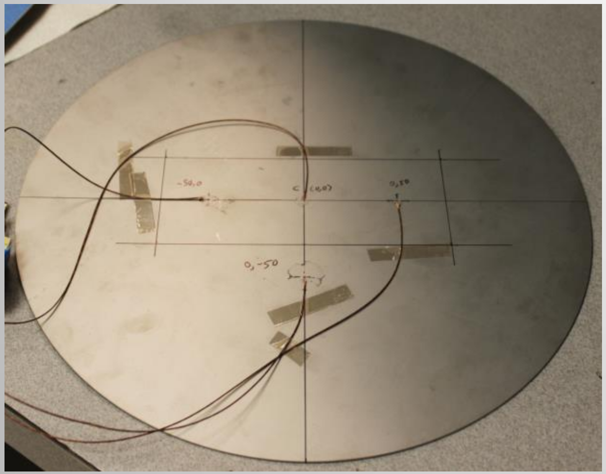
54.05 s

Results: Shape change of Al sheet due to heating (DIC)

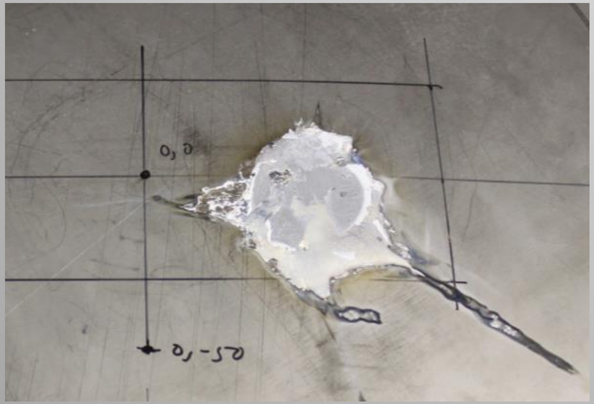
- Section at Y = 0



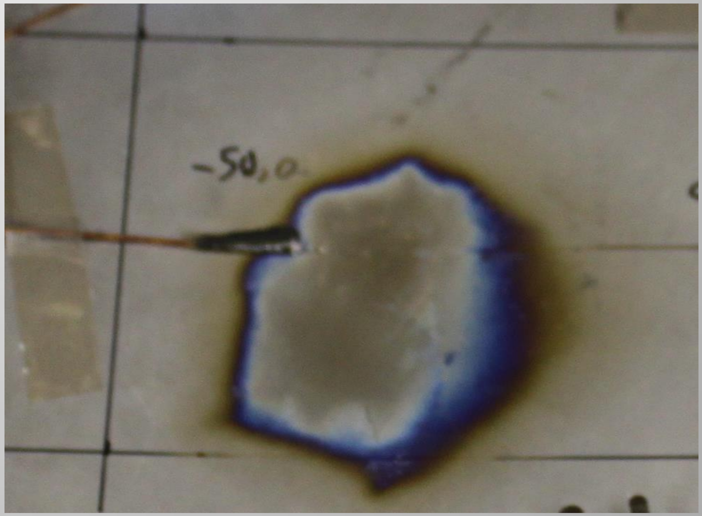
Results: Temperature rise in pressurized Ti plate due to molten aluminum (previous experiment)



- Rear side instrumented with type K, 36 gage thermocouples at locations (in mm): (0,0) (50, 0) (-50,0) (0,-50)



Aluminum melt on top side of Ti plate

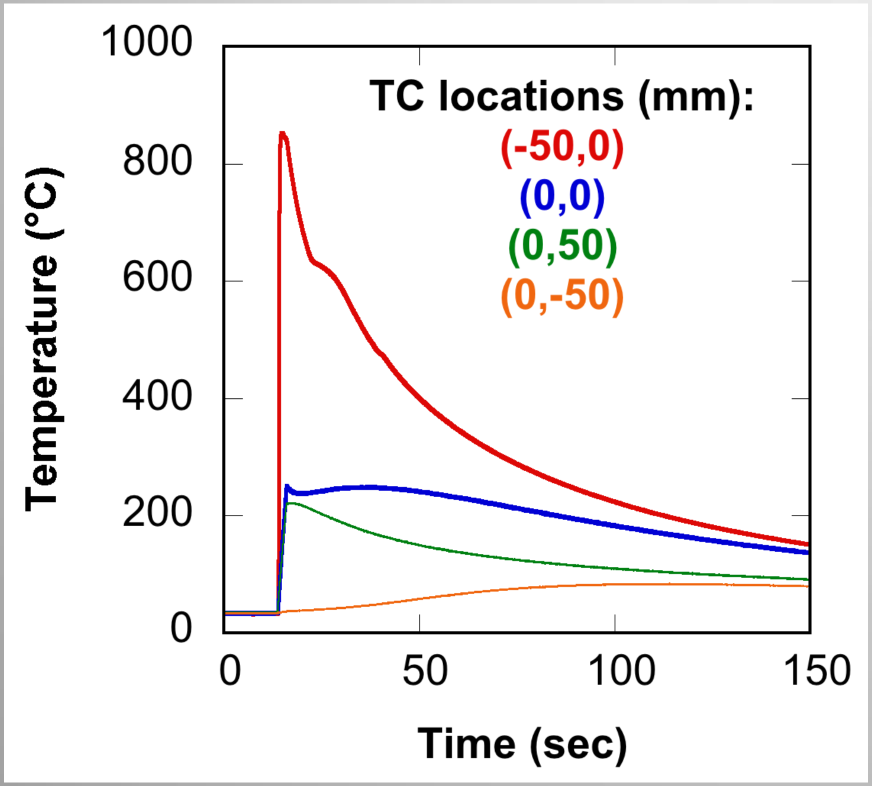


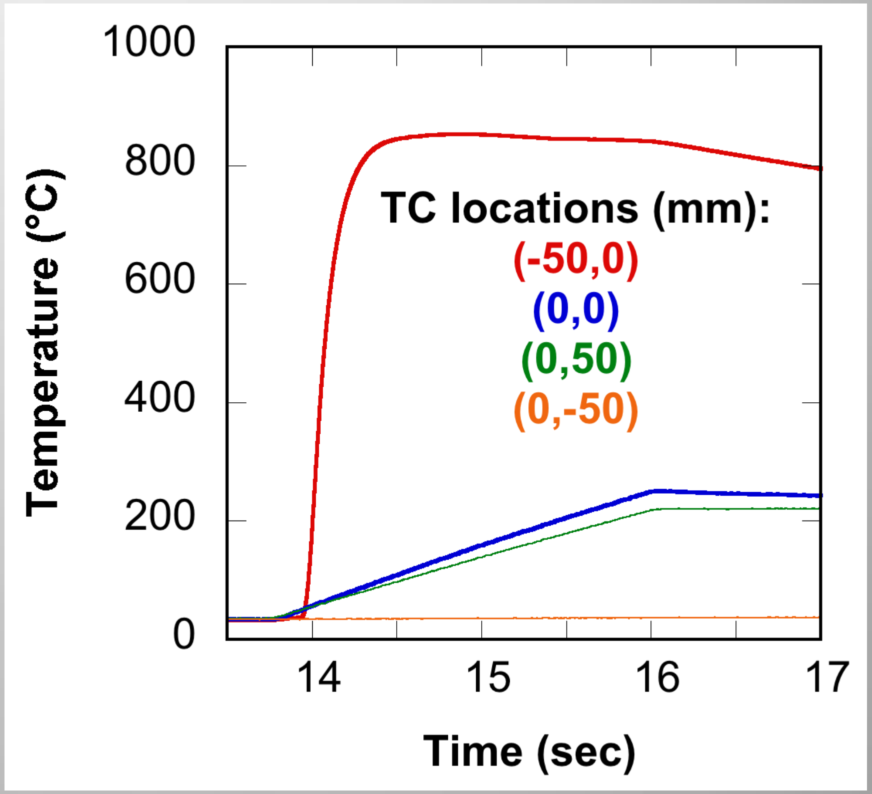
Discoloration of the underside of the Ti due to heat from molten aluminum

Results: Temperature rise in Ti plate due to molten aluminum

(previous experiment)

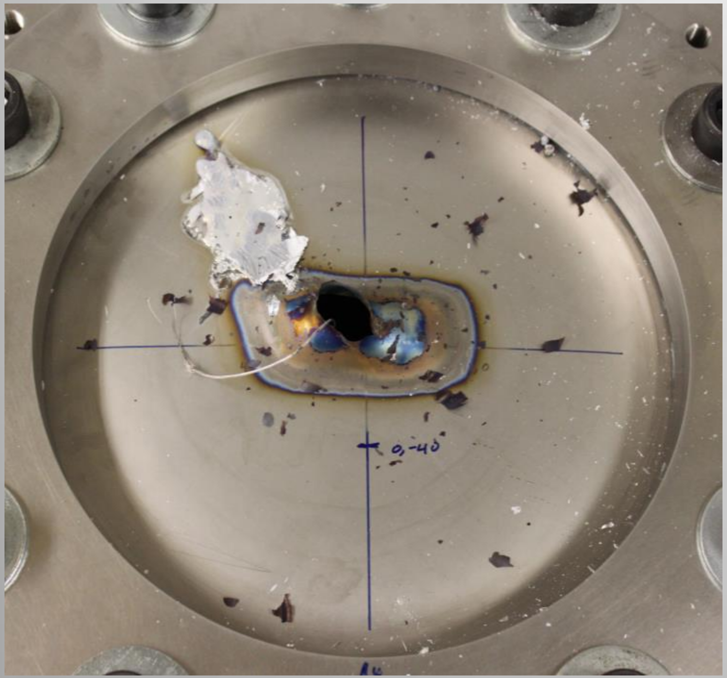
- All thermocouples remained attached

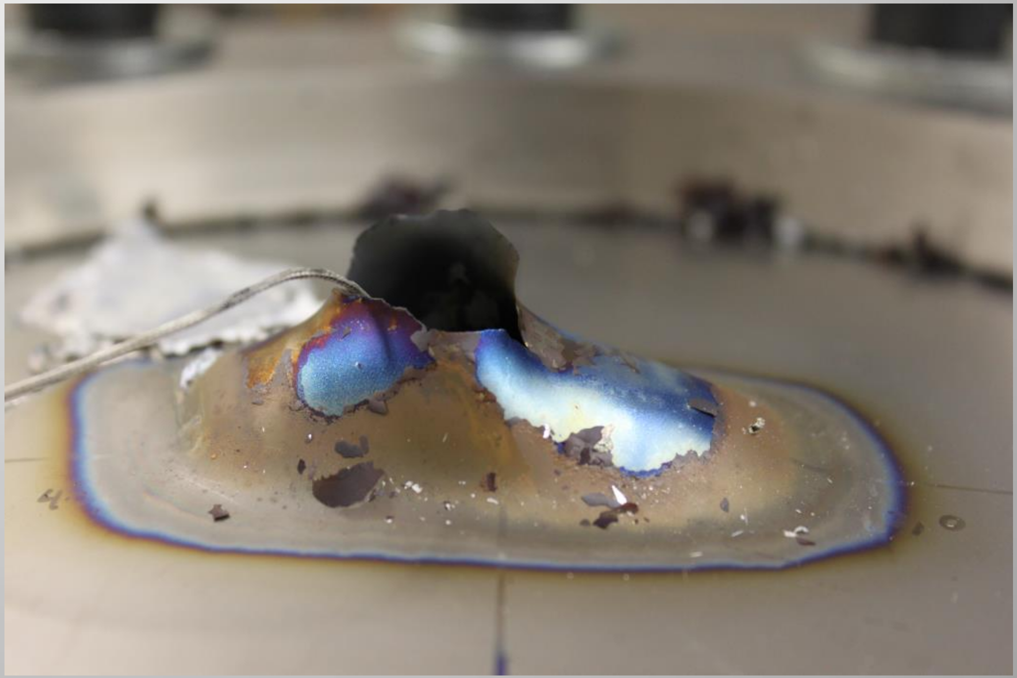




Results: Temperature rise in Ti plate due to laser

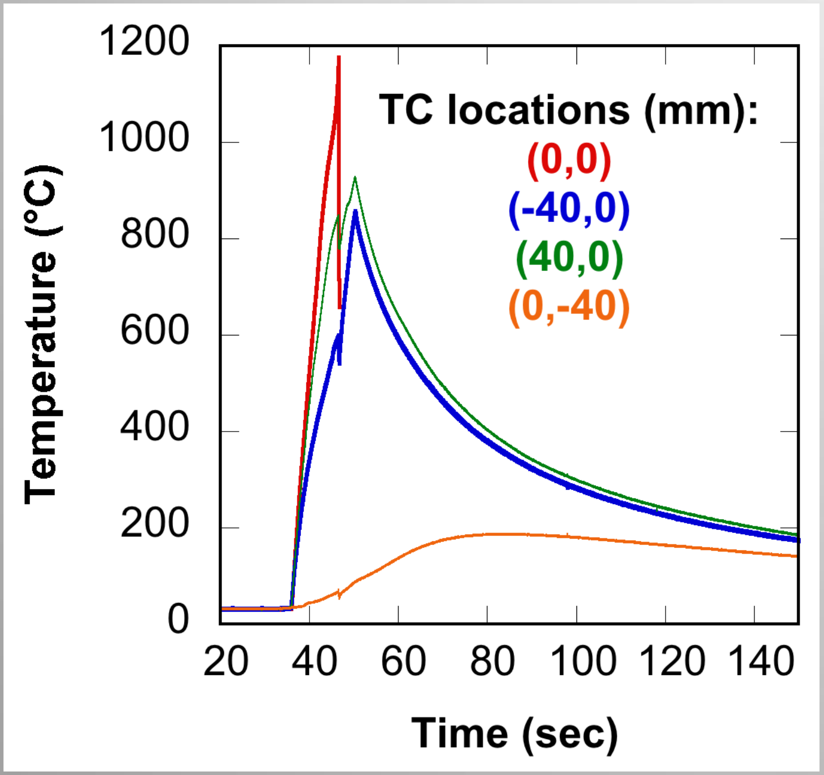
- After the aluminum melted and dripped, the laser heated a rectangular area on the pressurized plate until the plate ruptured

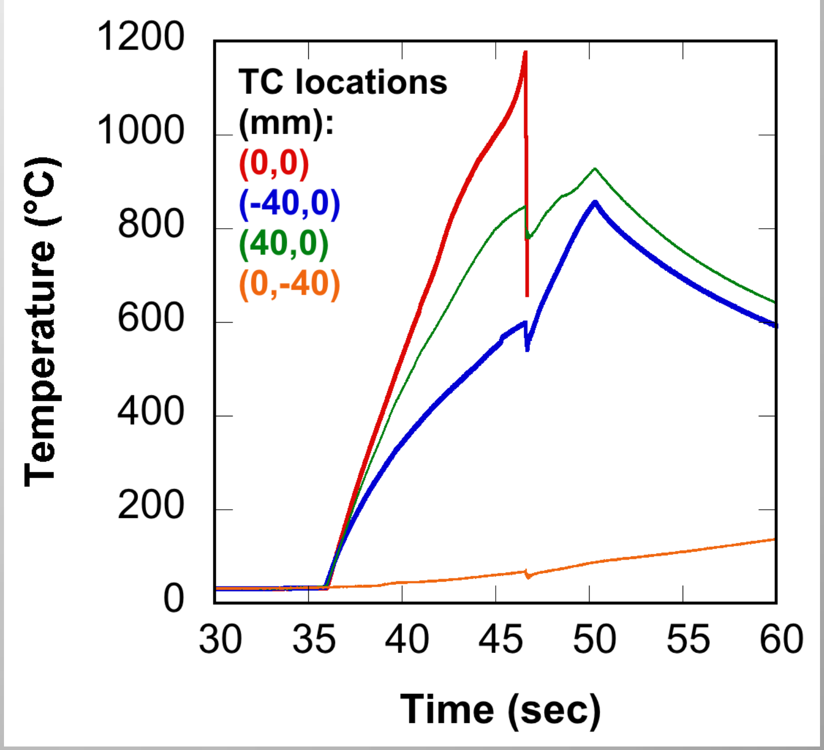




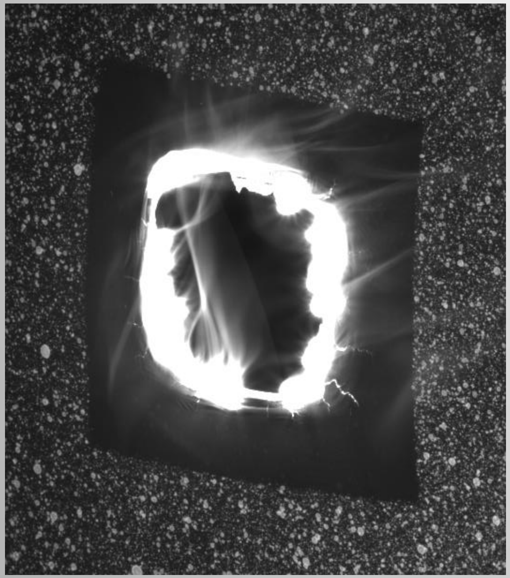
Results: Temperature rise in Ti plate due to laser

- Center temperature at rupture: 1175°C
- Center thermocouple failed at rupture; the other three remained attached





Results: Effects of Ti rupture on Al sheet



- Al plate just before rupture of the Ti vessel showing a region of softened or molten material

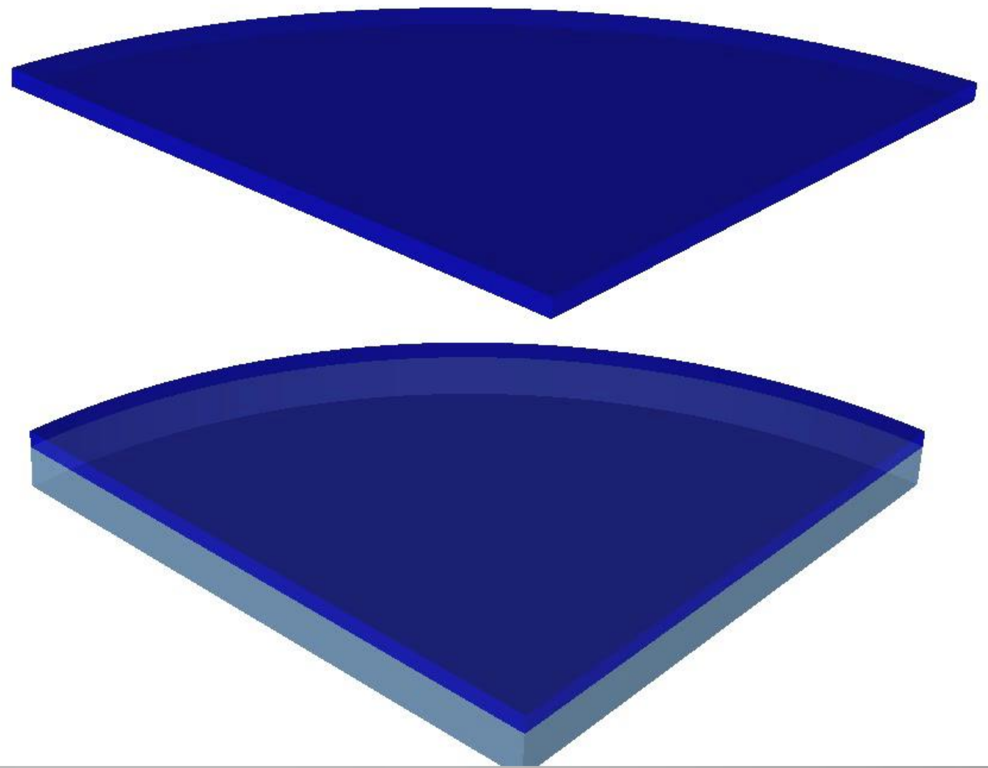
- Front side of the aluminum plate after the test. The rupture of the Ti vessel removed the melted material around the edge

- Rear side of aluminum plate showing molten Ti sprayed on surface

ALE3D models physics processes that drive laser-induced melt dynamics

- LLNL's ALE3D code includes elasto-plastic deformation before melting
- Melt hydrodynamics including temperature dependent surface tension, viscosity and recoil pressure
- Code is able to describe large displacement including spattering and droplets formation

Laser Power 4.4 kWatt uniform square (2 cm^2) spot



Conclusion

- Experiments on laser illuminated Al samples at intensities up to 200 W/cm^2, levels that are much lower than those in typical laser lethality studies found in literature
  - At intensities less than 150 W/cm^2, rapid formation of a thin oxide layer can prevent aperture clearing
  - At higher intensities, melt formation and penetration is governed by surface tension and gravity
  - No melt dispersion – ejected material comes out as big piece(s), rapidly and effectively clearing the laser pass
- Experimental demonstration the laser penetration of Al plate and subsequent rupture of a Ti pressure vessel
- Predictive modeling effort for laser-material interaction phenomena under constrained or stressed mechanical states
- Multiphysics code including laser energy deposition, material damage and oxidation, mechanical failure, melt evolution and aperture clearing.

Main physics processes that drive laser induced melt dynamics

Horizontal motion

Surface tension coupled to strong ***temperature gradients*** drive the ***Marangoni effect*** which causes the melt to retract horizontally away from the hot spot.

Vertical motion

The ***vapor recoil pressure*** imparts a vertical impulse in the direction of the laser beam. This vertical motion is enhanced by **gravity** which becomes more evident over time (>1ms).

Optimizing the laser rupture parameters

Limits on laser spot size parameter

- Keeping the laser power constant and doubling the laser spot size creates a ***larger window*** for the laser to penetrate and cause further melting.

- However, nature tends to minimize the surface energy which leads to breakup of large melt surfaces into small particulates. The latter can act as ***obstacles*** to the laser penetration.

Laser Power 4.4 kWatt uniform square (4 cm^2) spot